National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

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Base Heating Test: Environments and Base Flow Physics

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Outline

- Motivation and Focus
- Base Flow Physics and Considerations
- Design Environment Method
- Base Heating Test Data
- Design Environments
- Conclusions

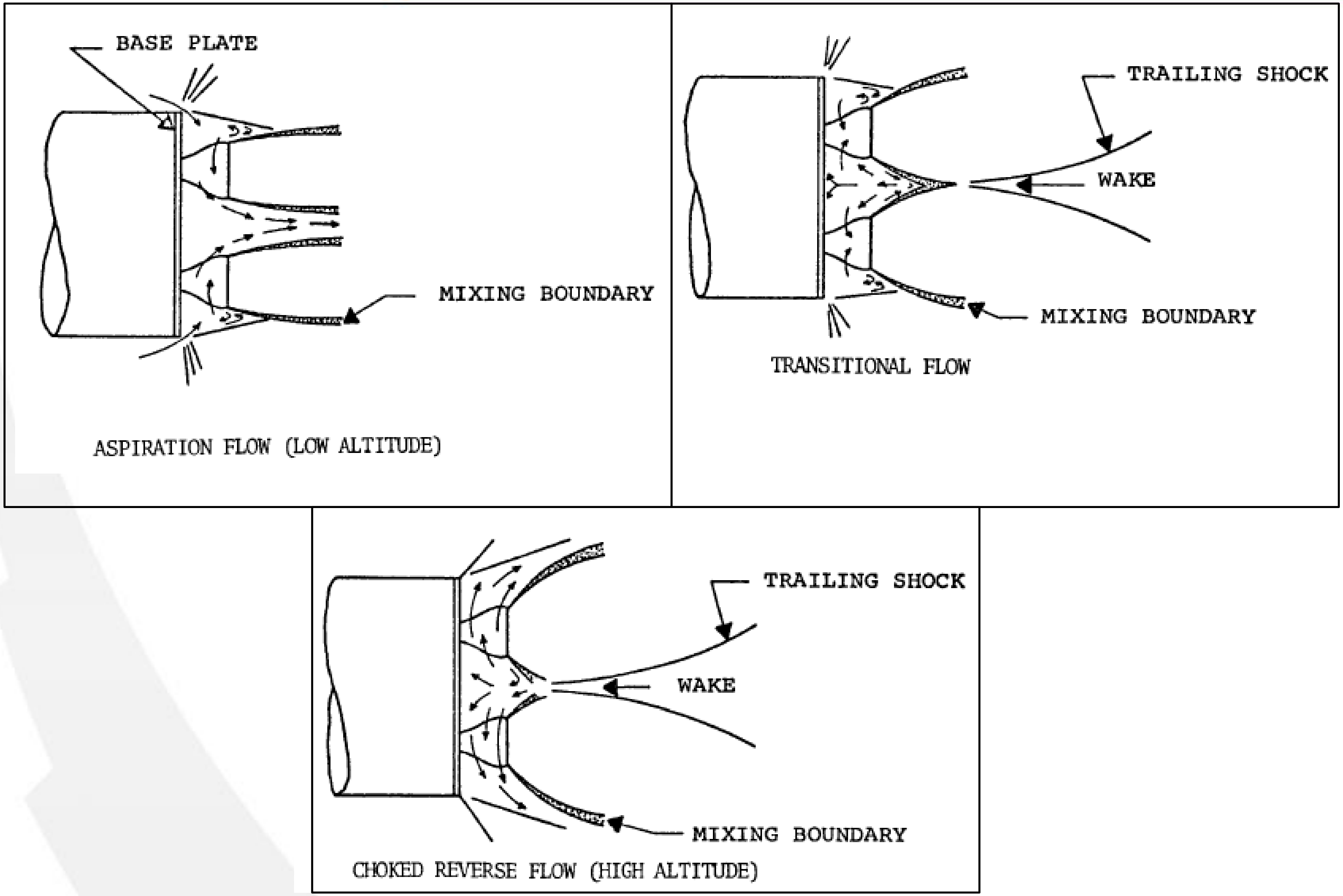
Motivation and Focus

- **Not able to generate accurate Space Launch System (SLS) base heating design environments without ground test due to:**
  - Historic semi-empirical models based on different aft configurations than SLS (e.g. Shuttle, Saturn)
  - Lack of analytical solutions to predict such complex flow physics

- **NASA MSFC and CUBRC developed a 2% scale SLS hot fire wind tunnel test program[1,2] to obtain ascent base heating test data.**
  - Such a test program has not been conducted in 40+ years since the Shuttle Program
  - Dufrene et al paper[3] described the operation, instrumentation type and layout, facility and propulsion performance, test matrix and conditions and some raw test results.

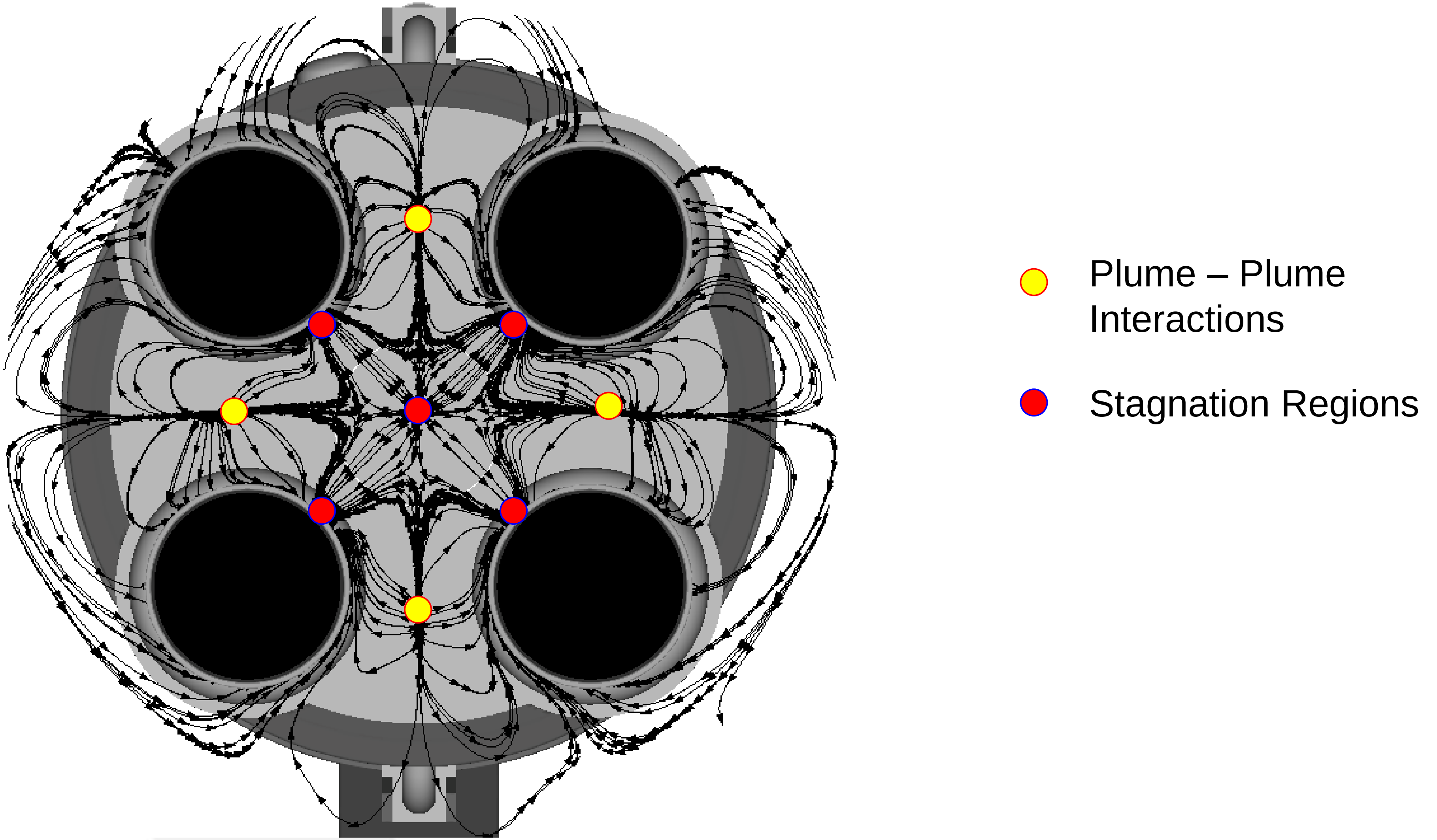
- **This paper focuses on the SLS base flow physics and environment results being used to design the thermal protection system (TPS).**

Base Heating Flow Regimes

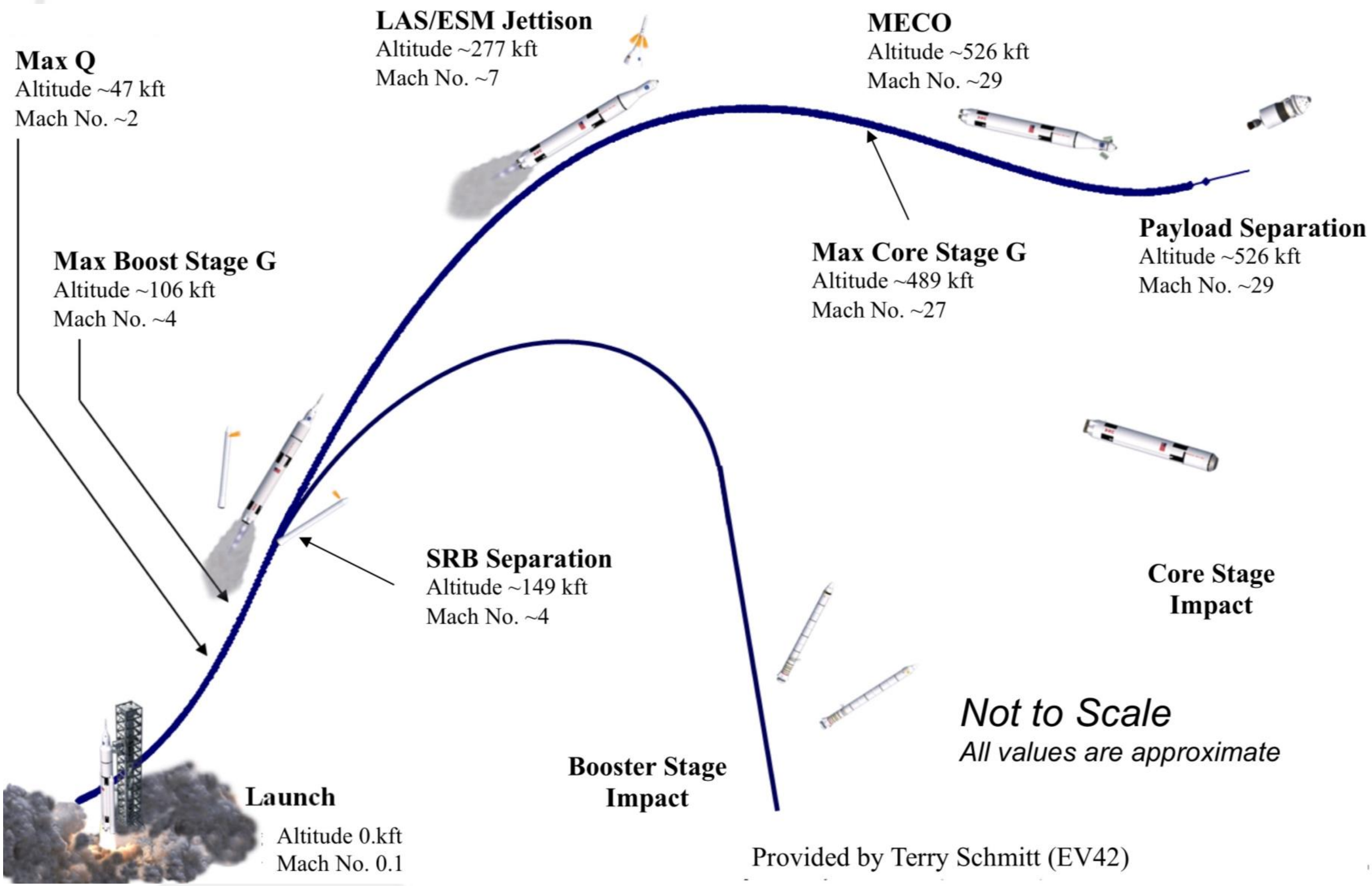


Mullen et al (1972)[8]

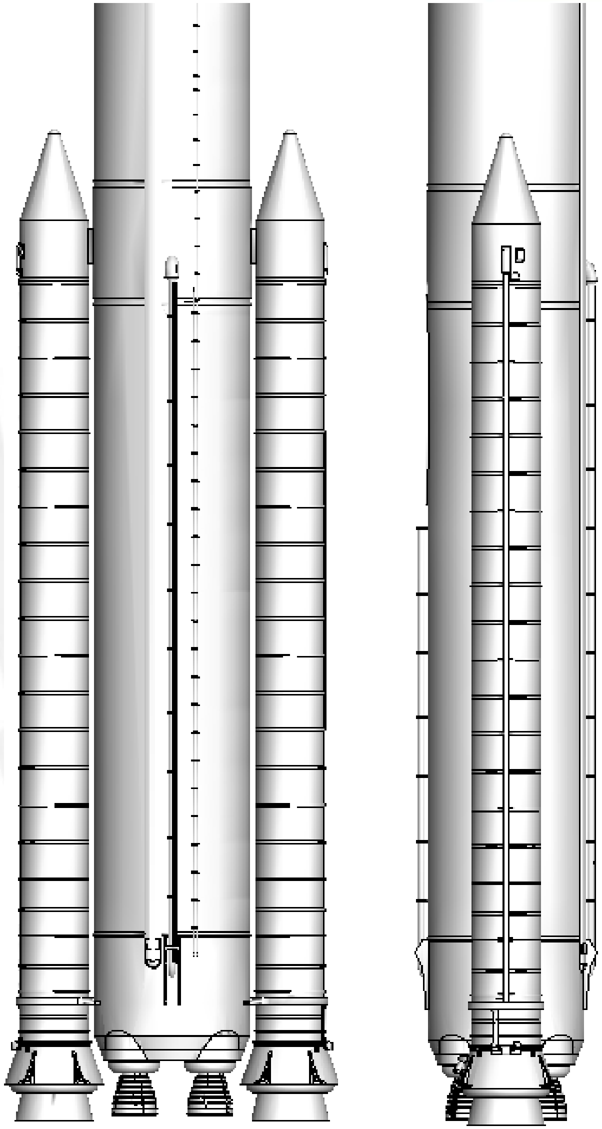
Base Flow Computational Fluid Dynamics

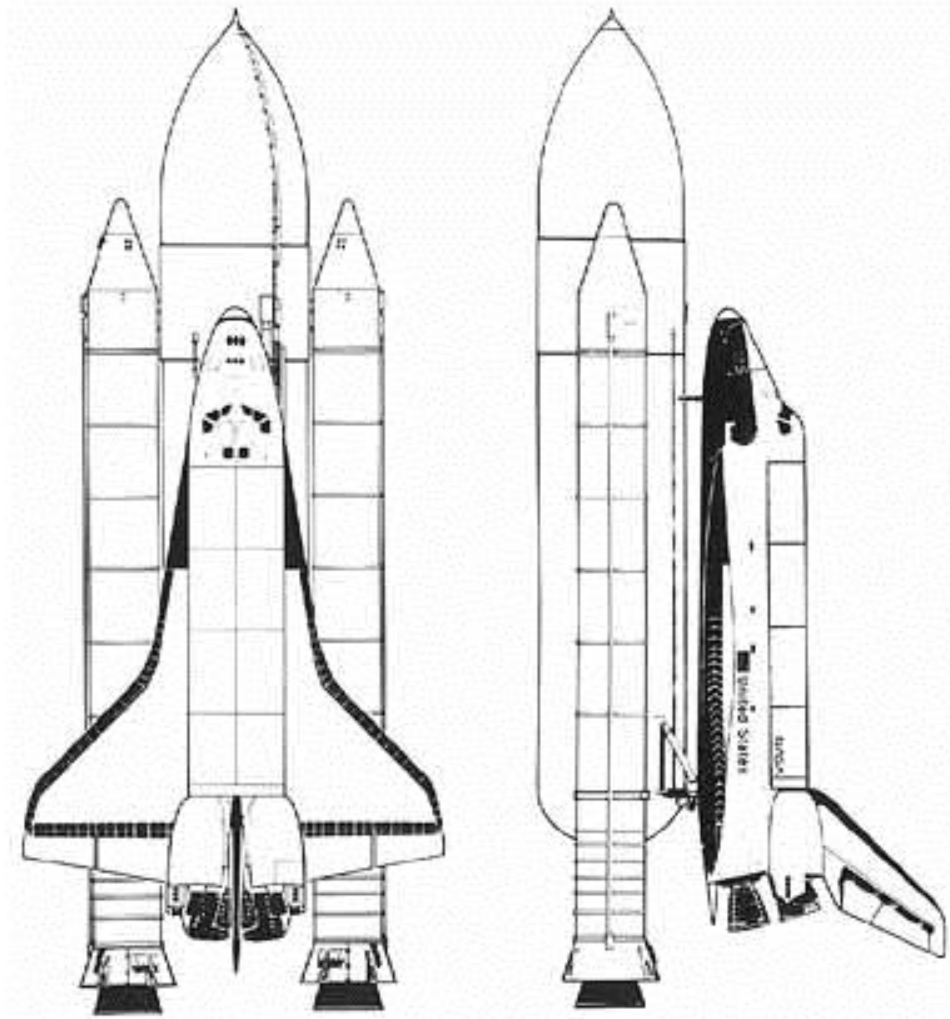


SLS Mission Profile

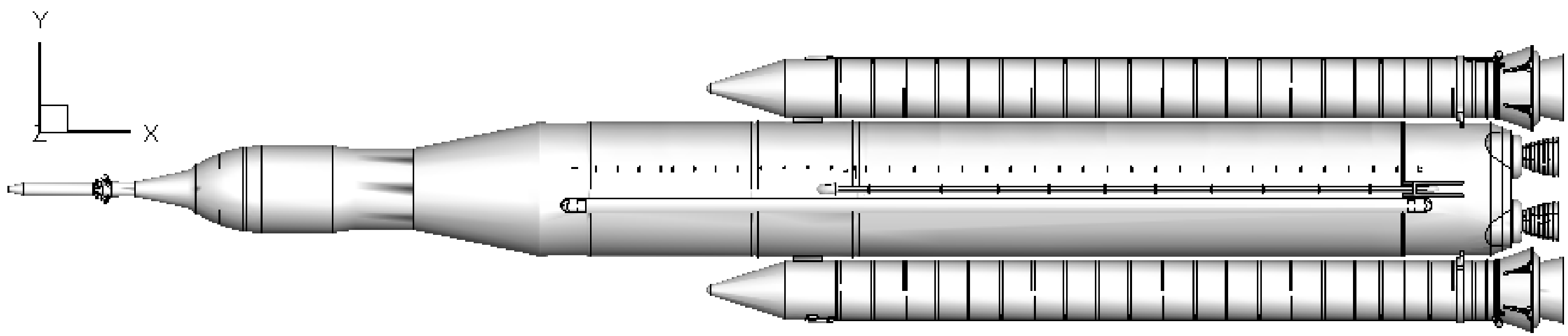


SLS vs Space Shuttle Base Configuration

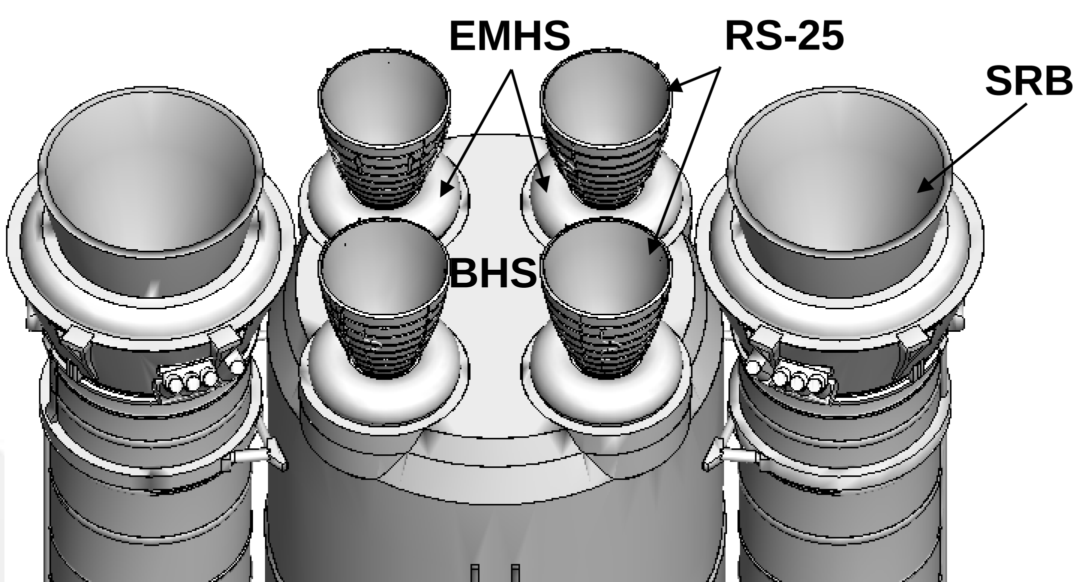




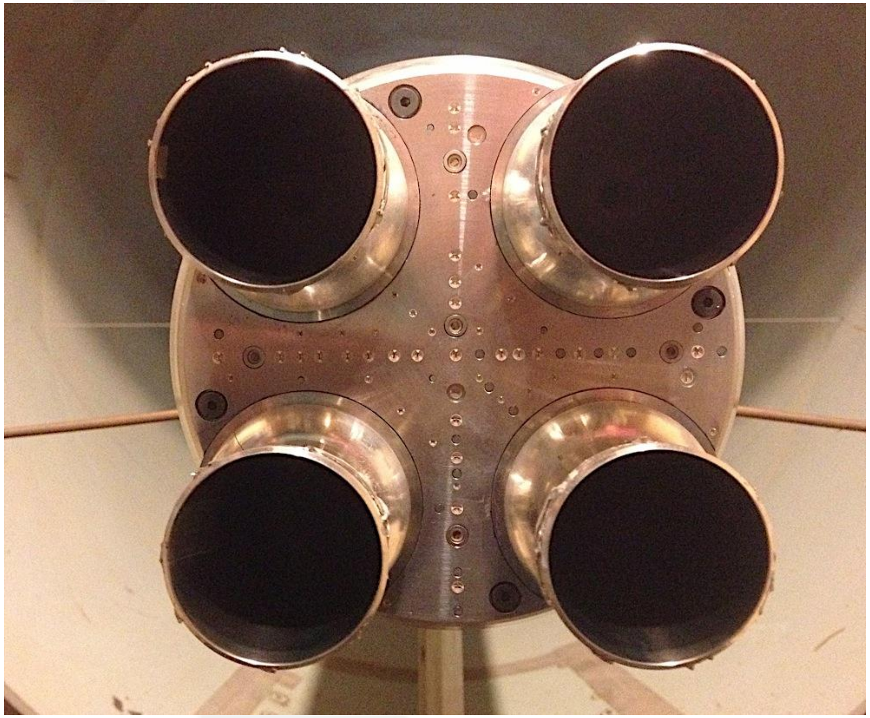
SLS Vehicle and Base Region

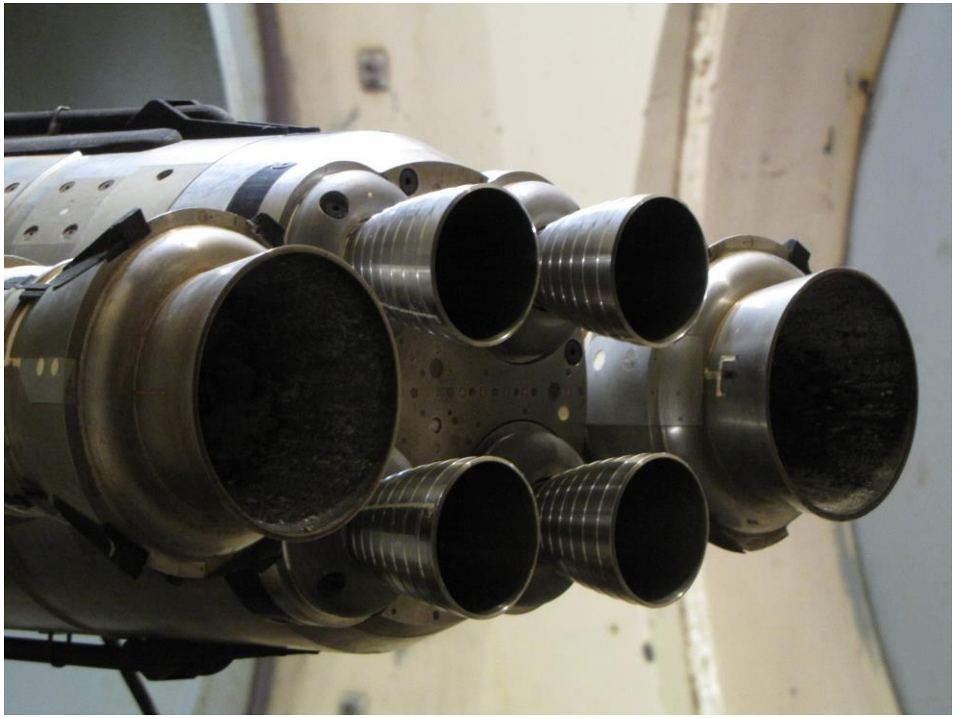


BHS – Base Heat Shield
EMHS – Engine Mounted Heat Shield
SRB – Solid Rocket Booster



ATA-002 Wind Tunnel 2% Scale Model

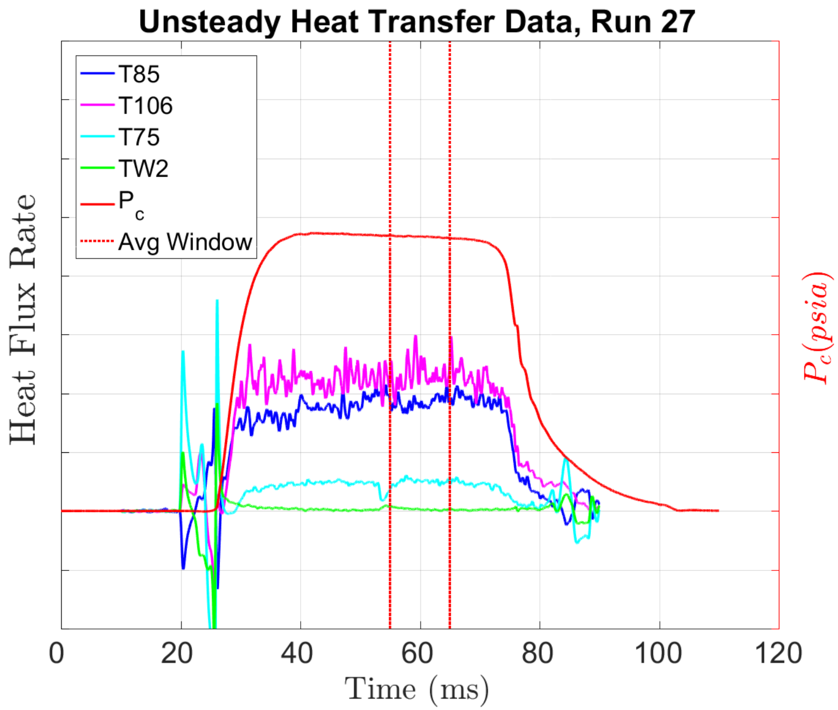


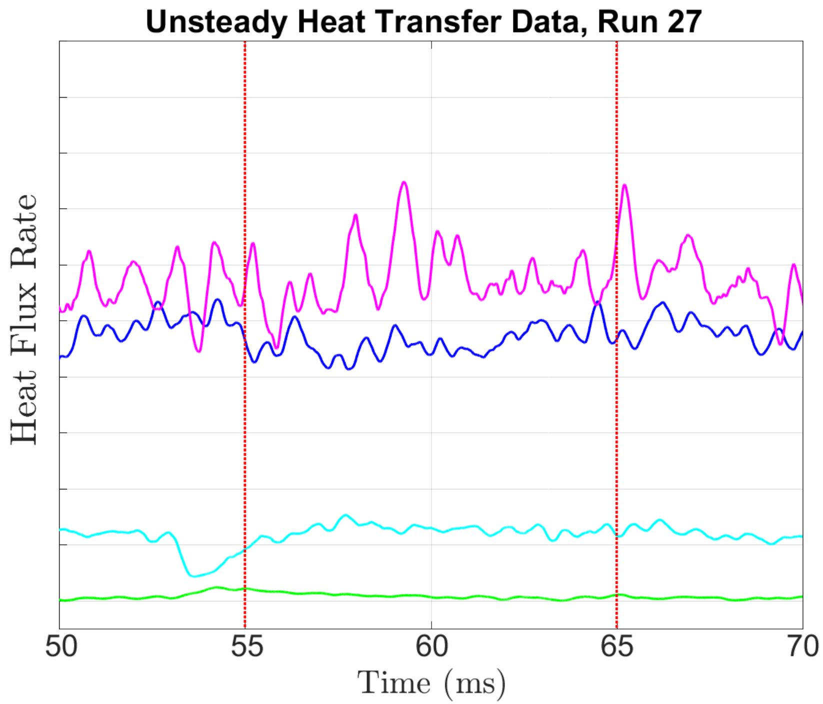


SLS Base Design Environment Method

1. Test Matrix Based on Flight Trajectory
2. Reynolds Scaling
3. Aspiration and High Altitude Models
4. Plume Radiation
5. Trajectory Dispersions and Events
6. Core Auxiliary Power Unit Heating
7. **Flight Design Environments**

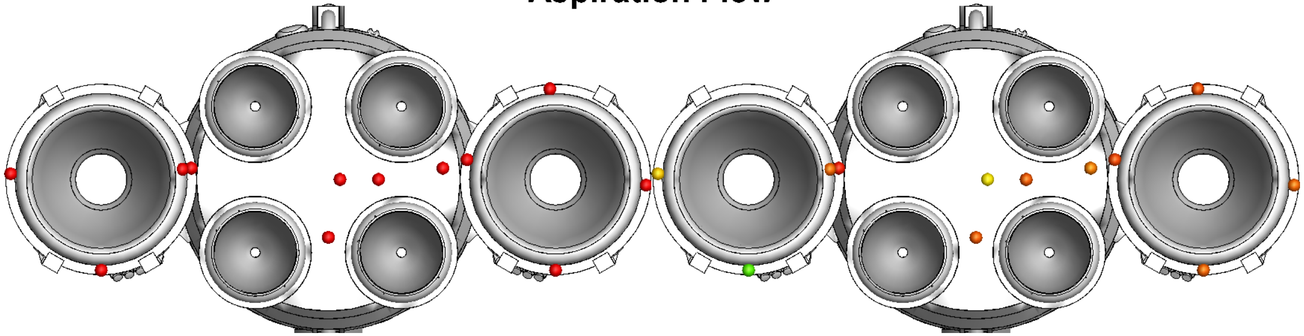
Unsteady Heat Transfer Data



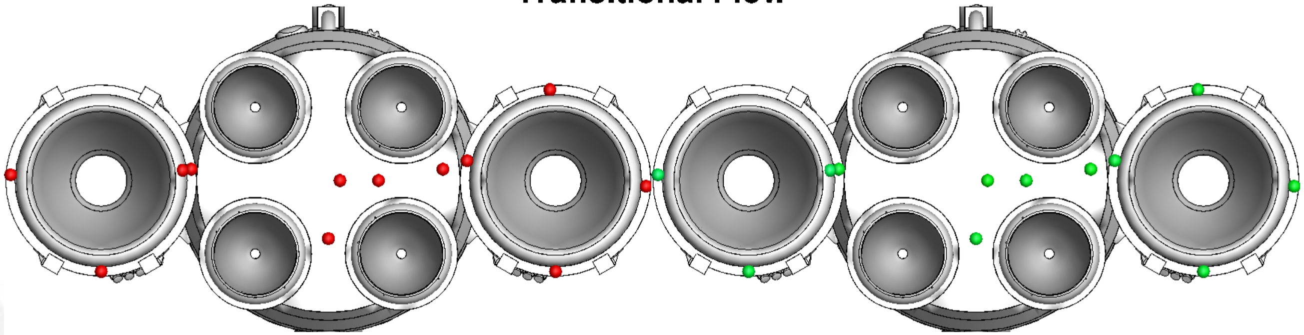


Base Heat Shield Pressure Maps

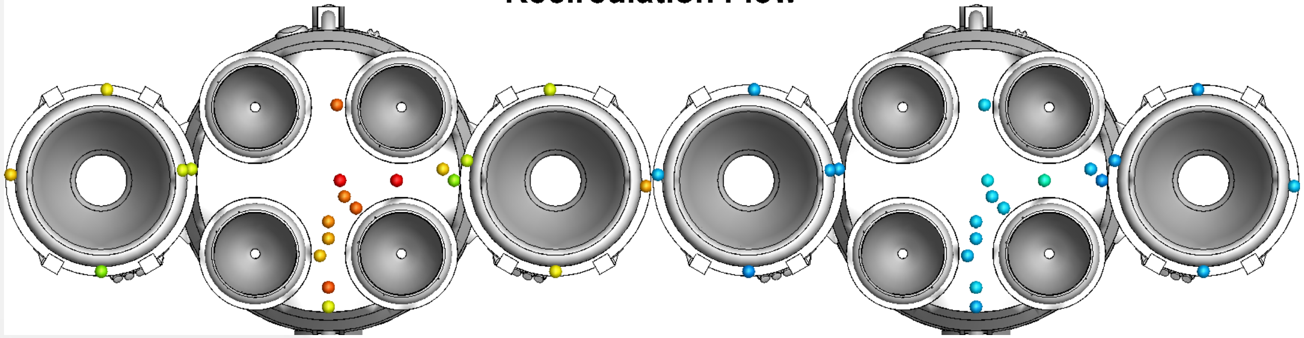
Alt: 50 kft
Aspiration Flow



Alt: 69 kft
Transitional Flow

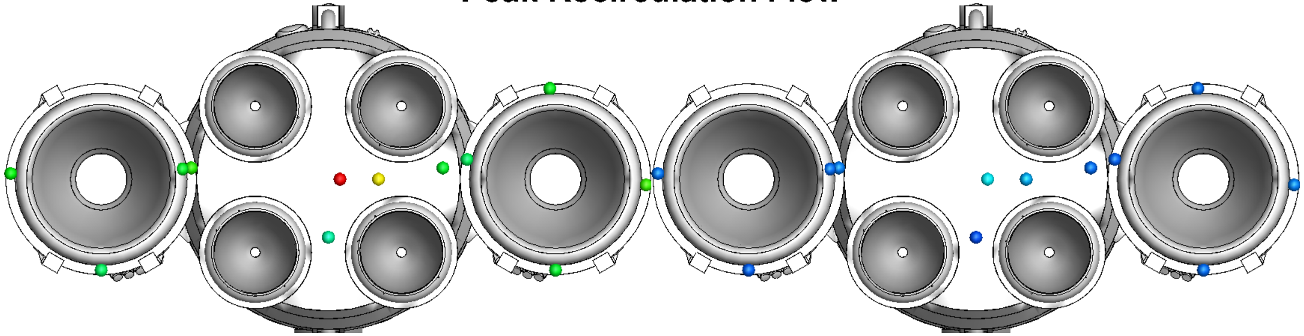


Alt: 107 kft
Recirculation Flow

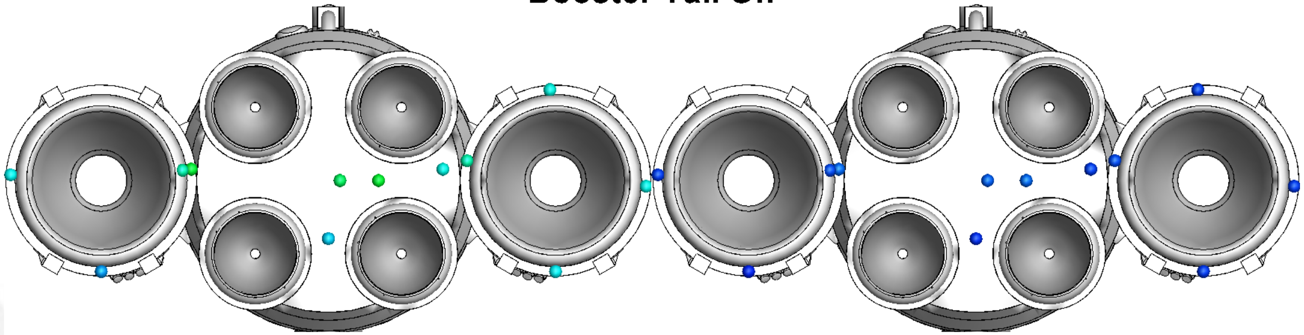


Base Heat Shield Pressure Maps

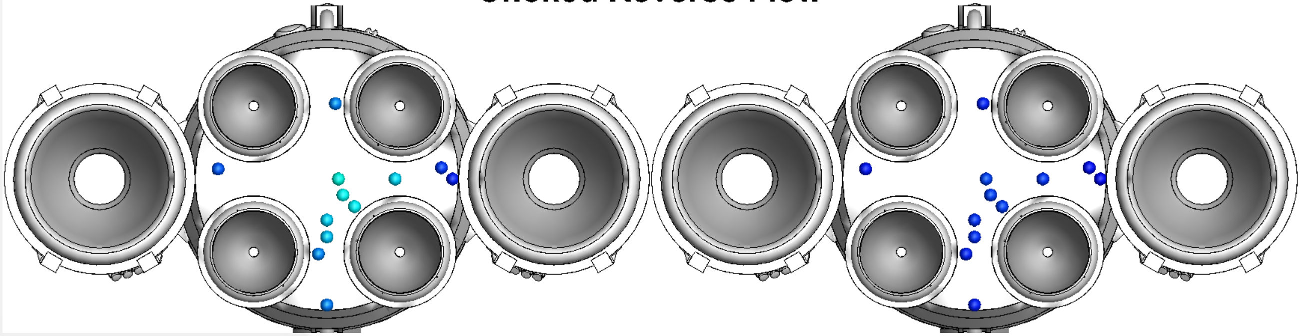
Alt: 121 kft
Peak Recirculation Flow



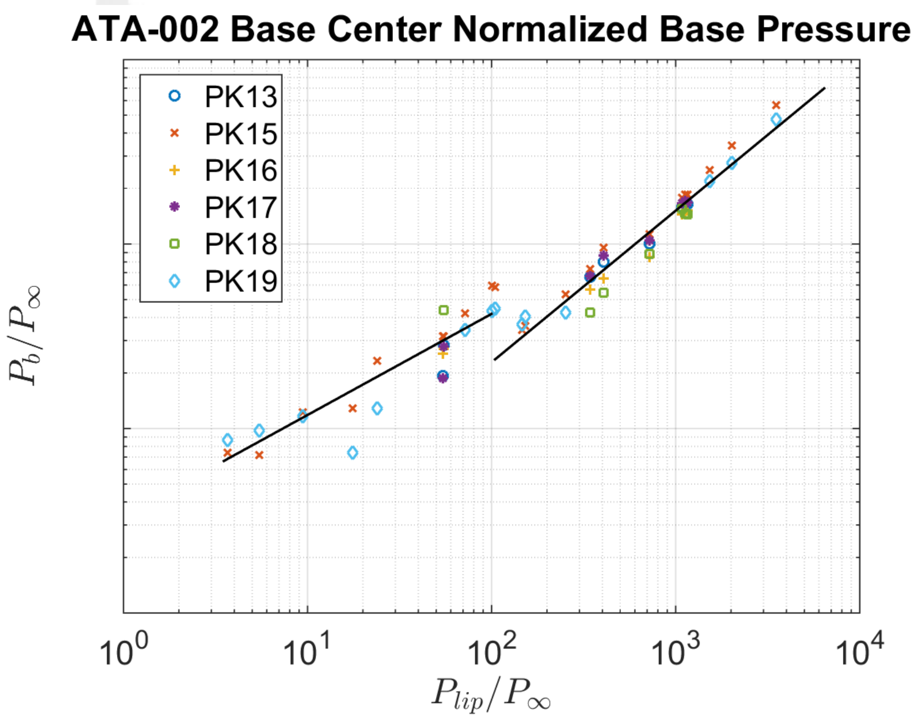
Alt: 131 kft
Booster Tail Off

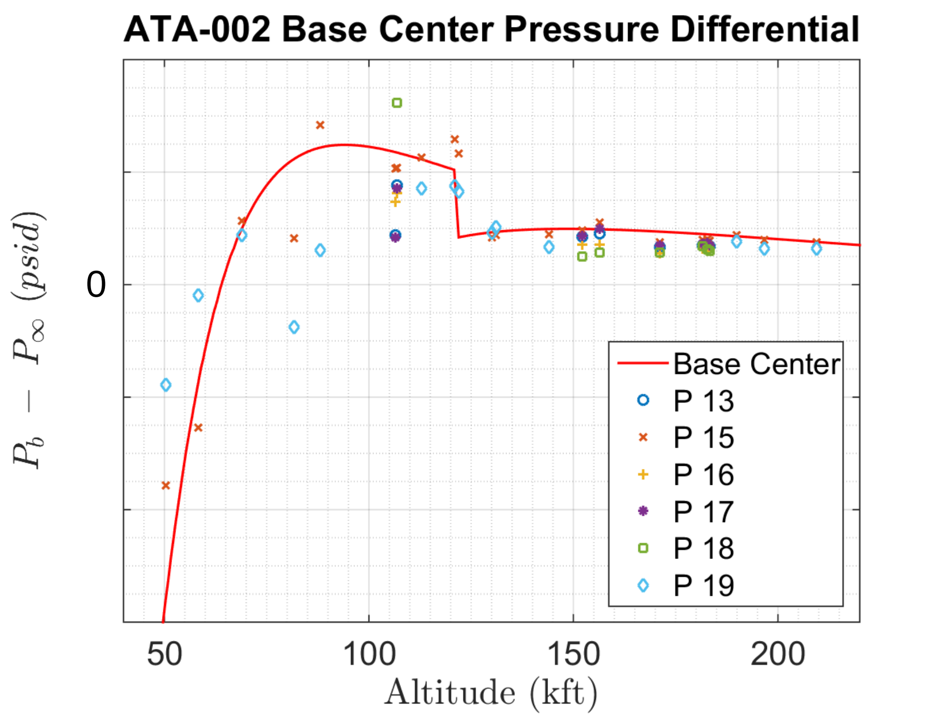


Alt: 171 kft
Choked Reverse Flow

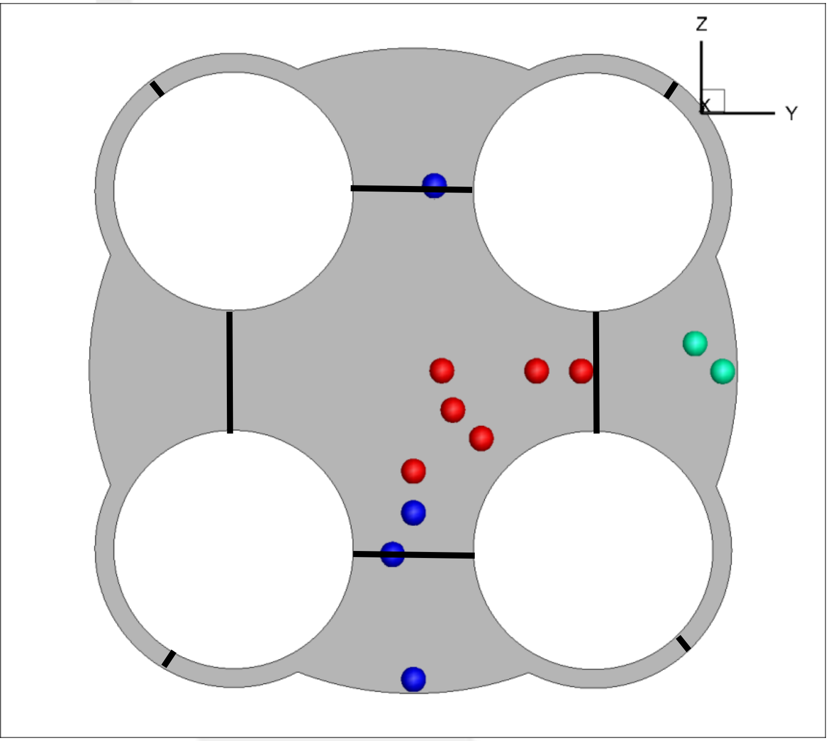


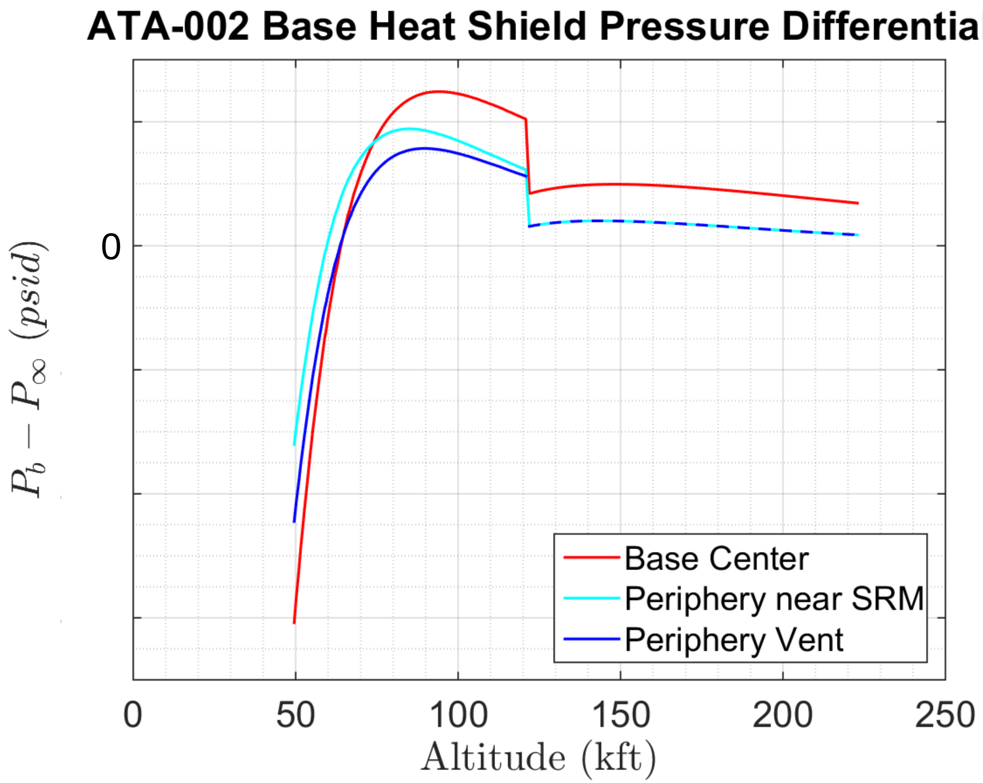
Base Center Pressure Differential



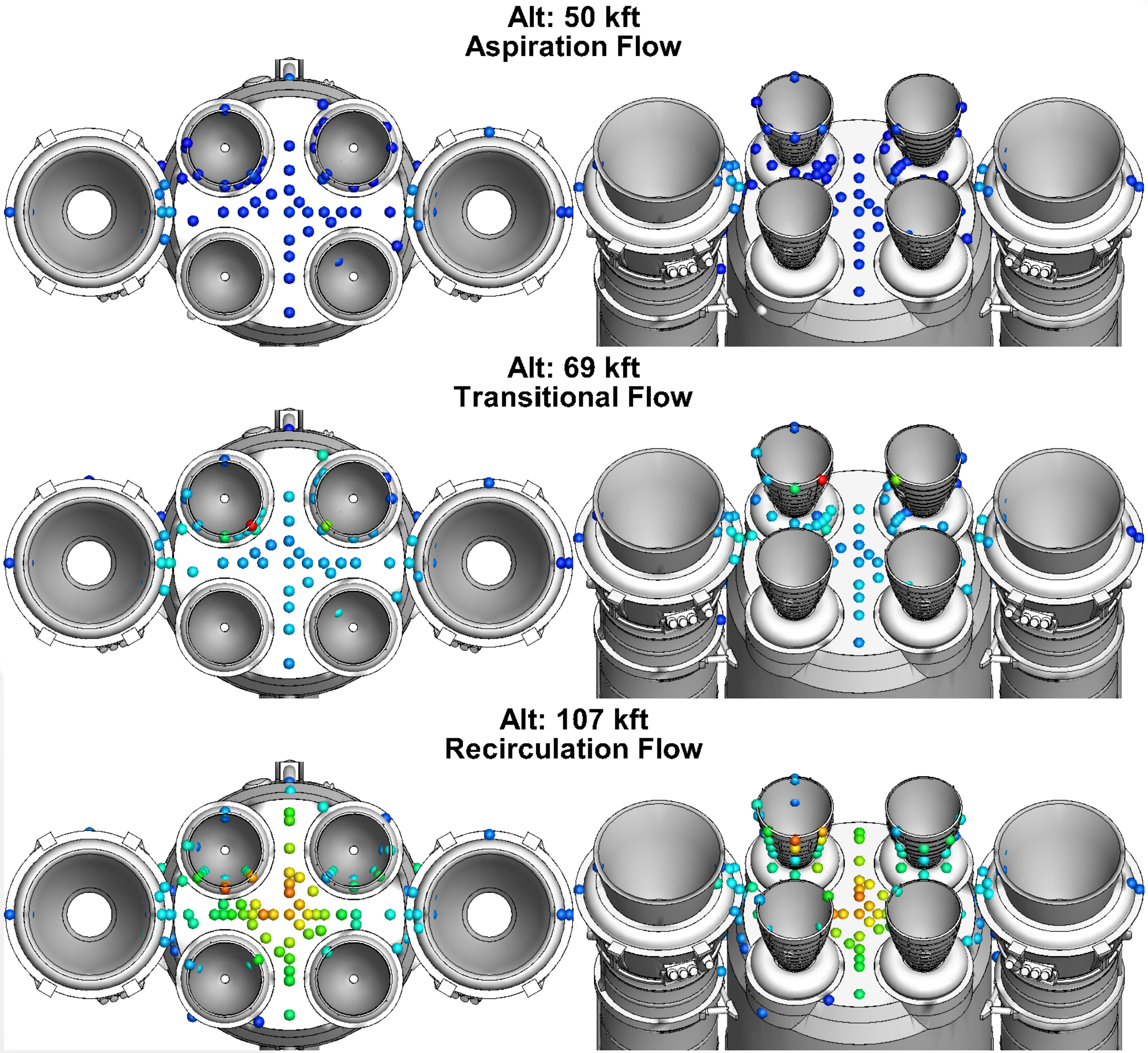


Base Heat Shield Pressure Differential



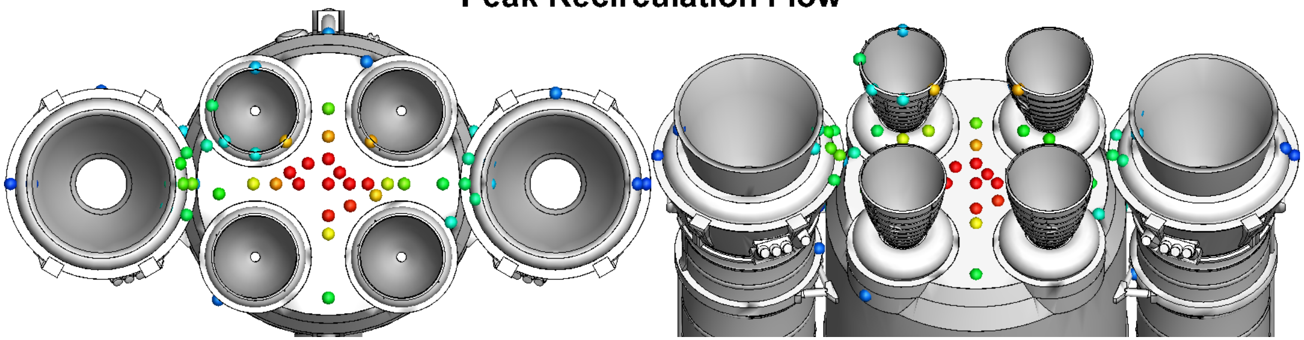


Base Heat Shield Heating Maps

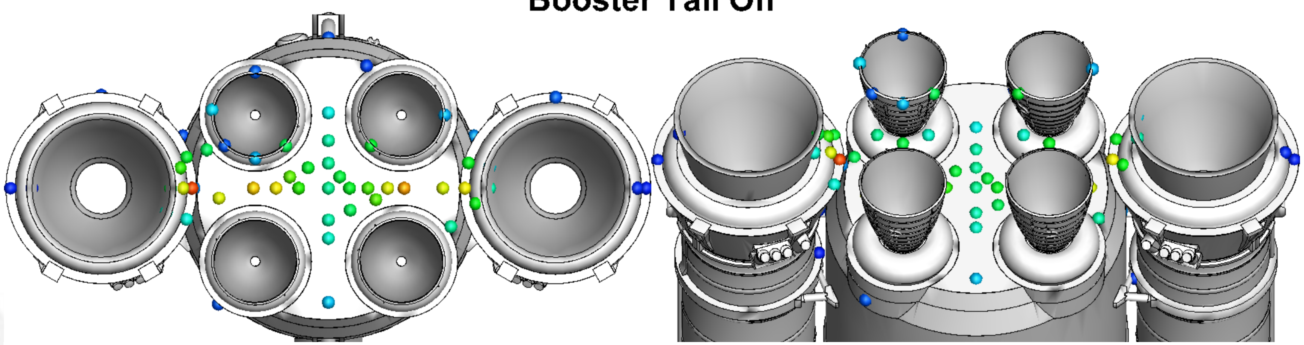


Base Heat Shield Heating Maps

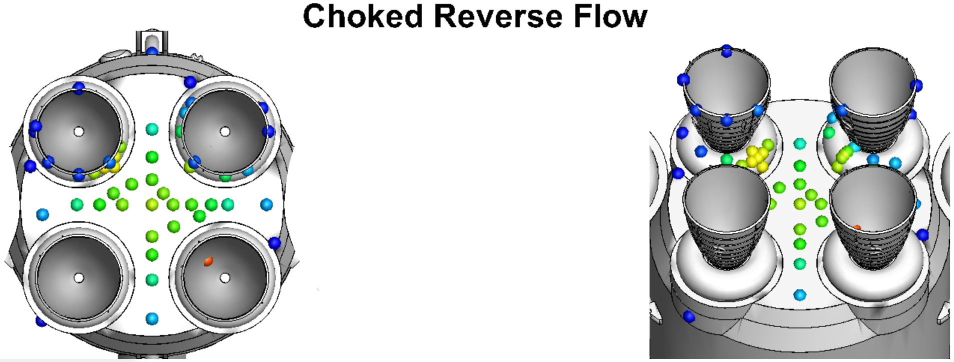
Alt: 121 kft
Peak Recirculation Flow



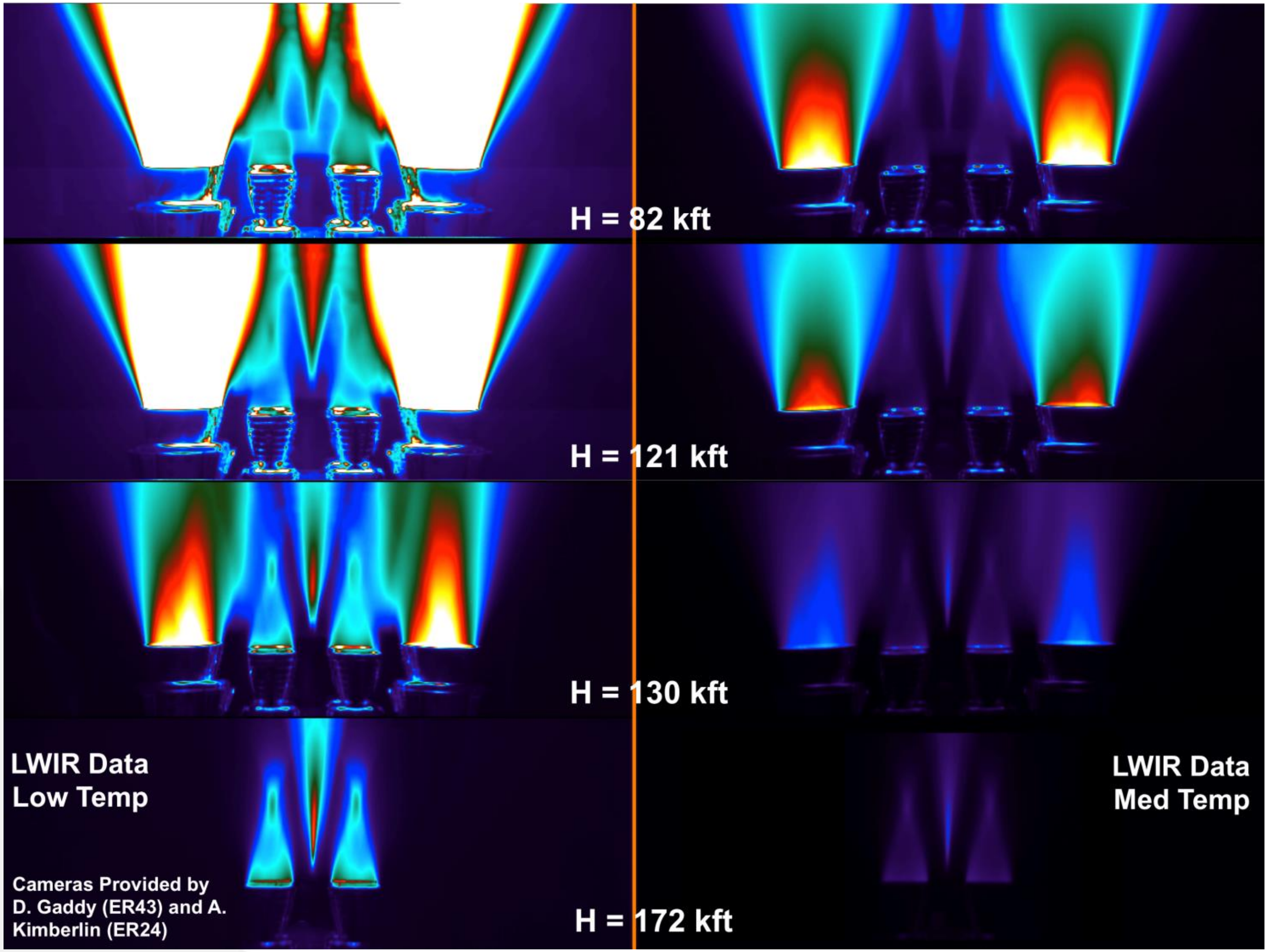
Alt: 131 kft
Booster Tail Off



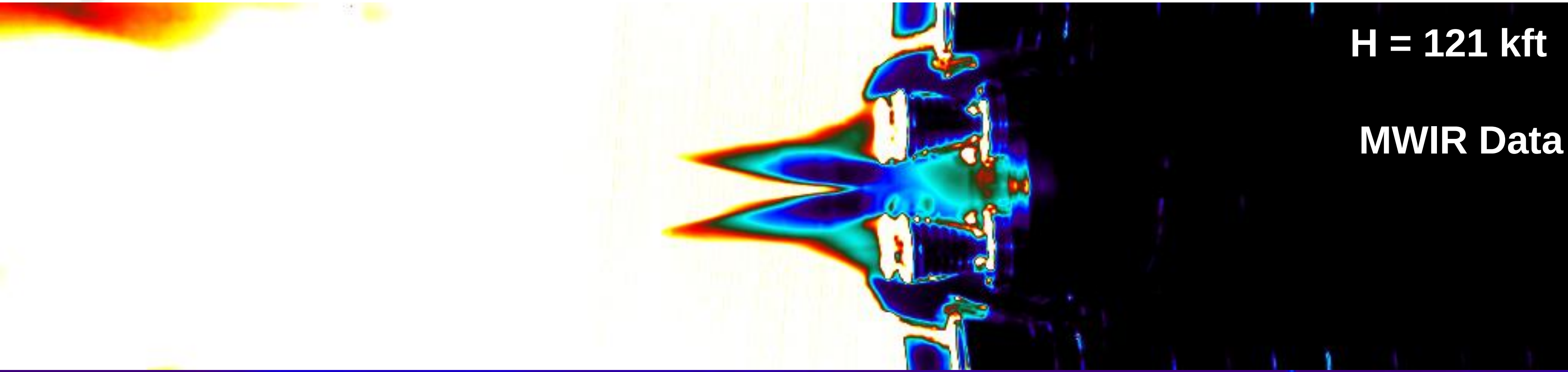
Alt: 209 kft
Choked Reverse Flow

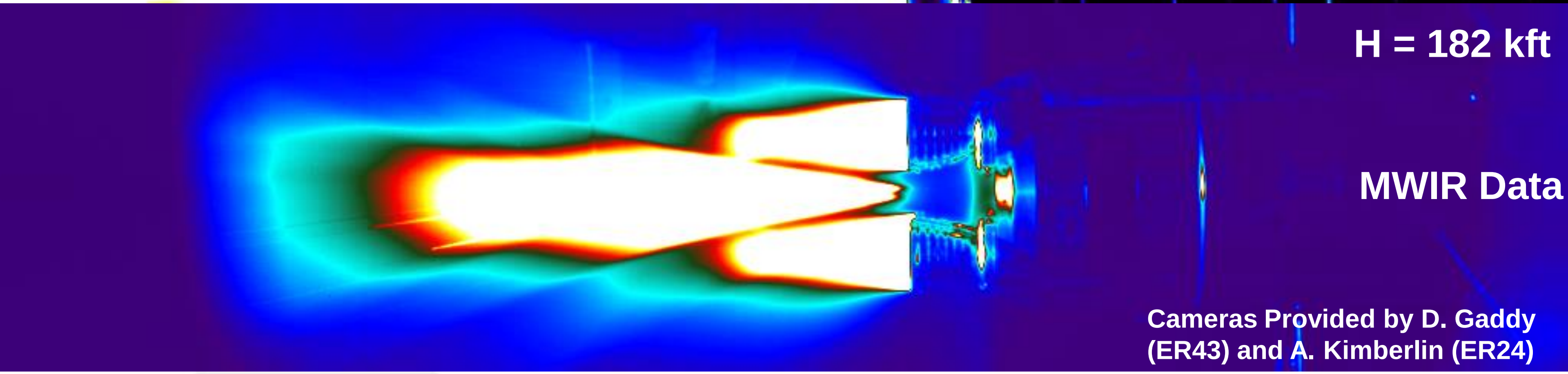


Long Wave Infrared Imaging

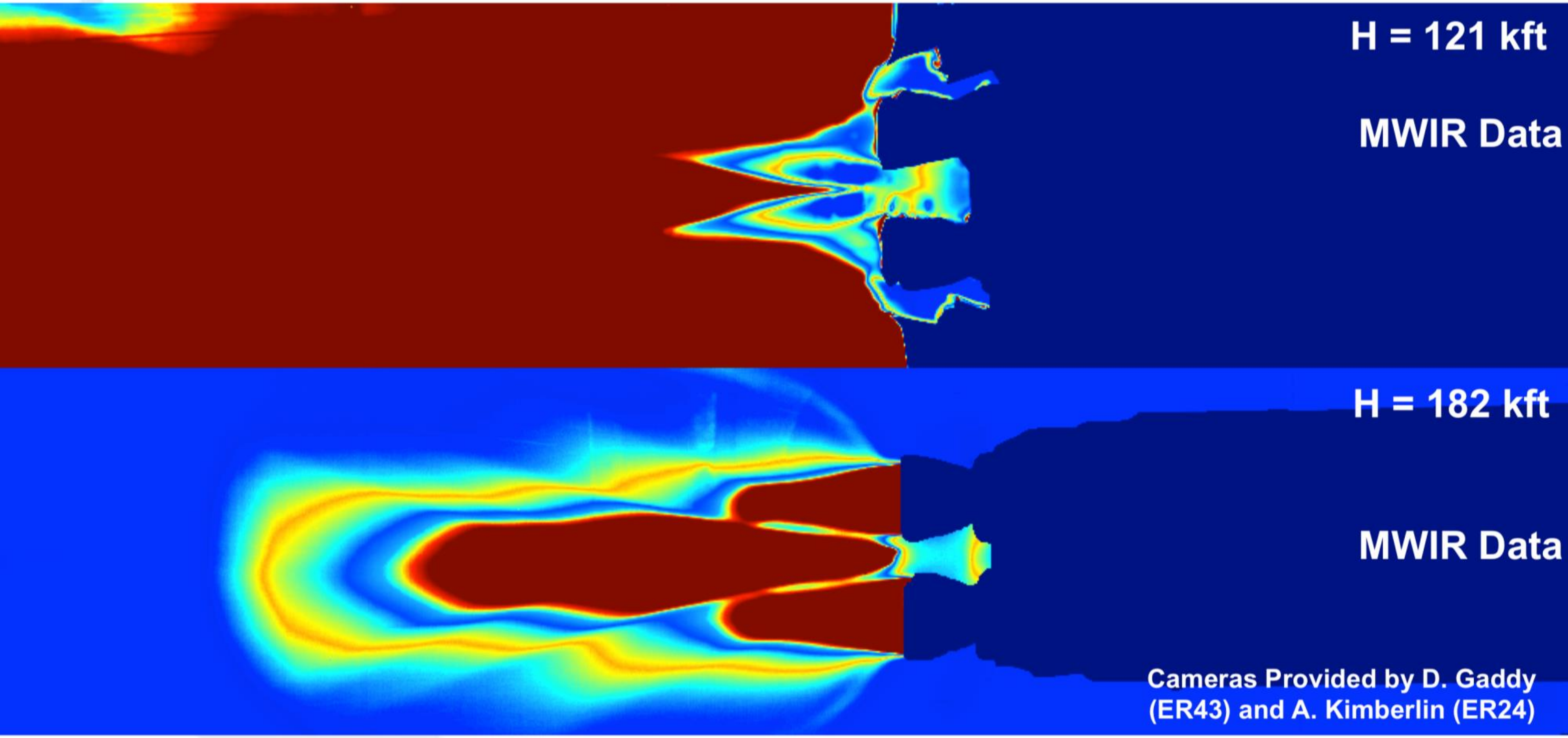


Mid Wave Infrared Imaging

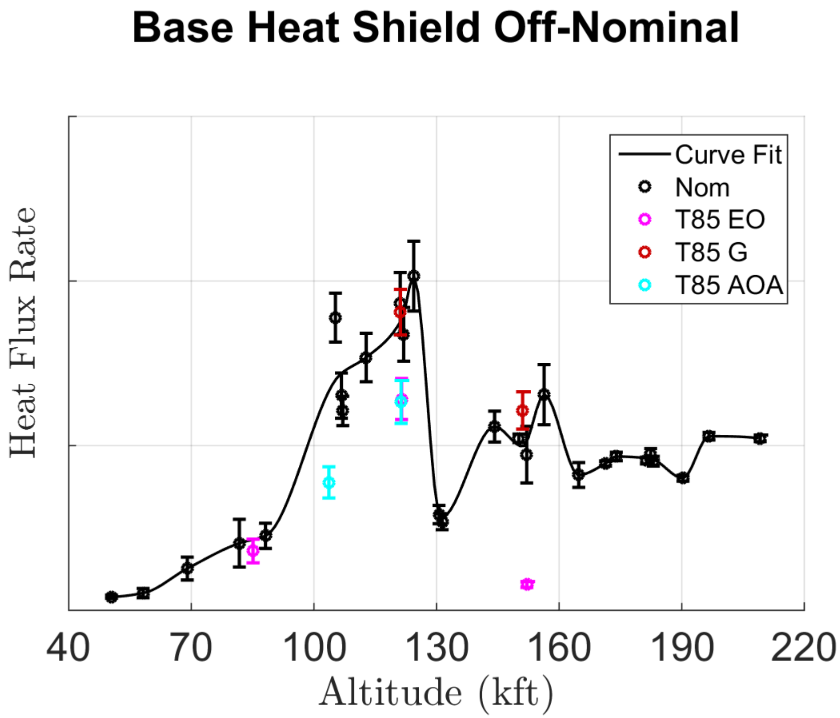


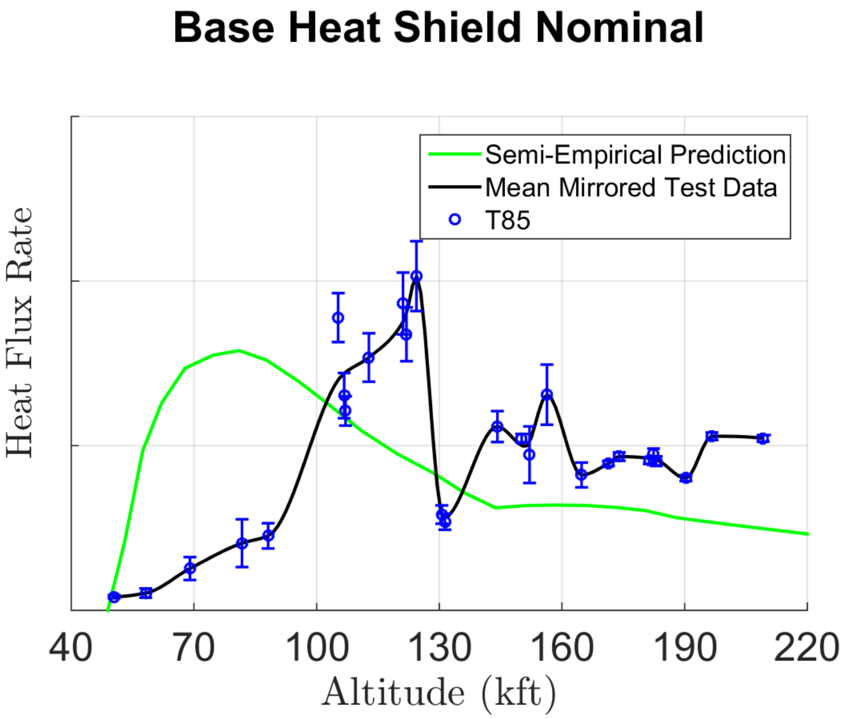


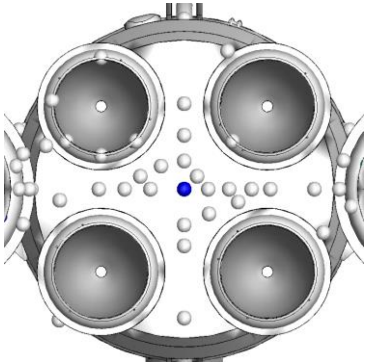
MWIR Masked Imaging



Base Heating – Altitude Profile: BHS Center

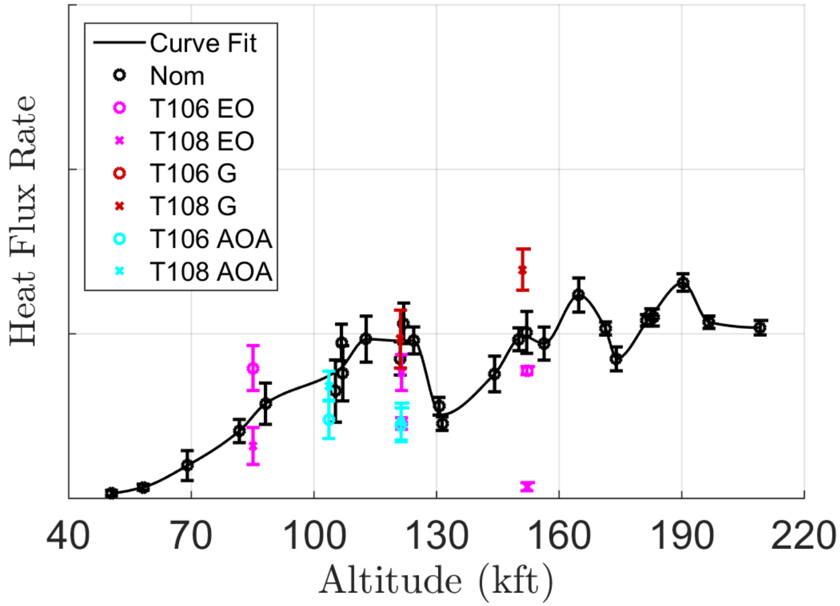




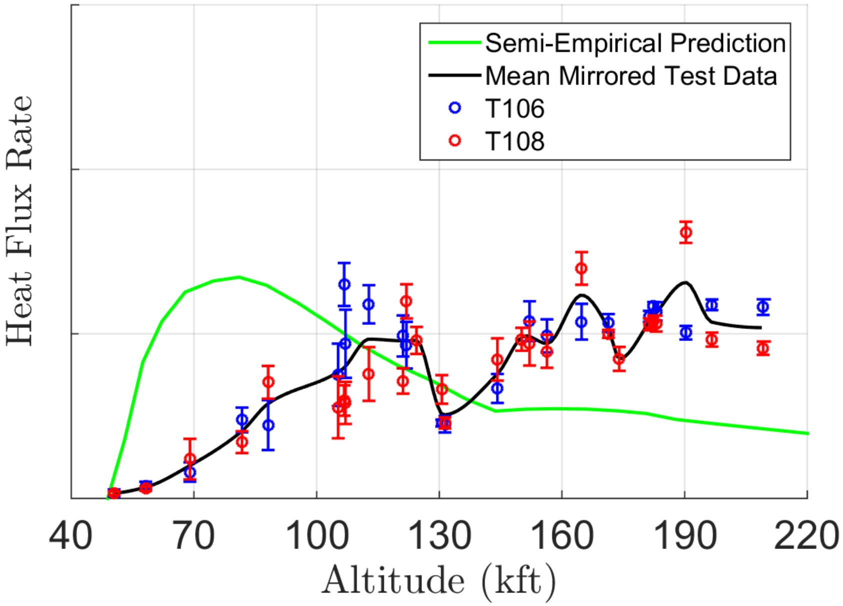


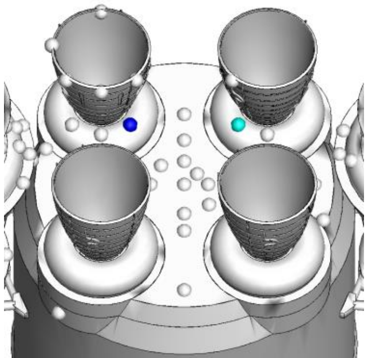
Base Heating – Altitude Profile: Inboard EMHS

Engine Mounted Heat Shield Off-Nominal



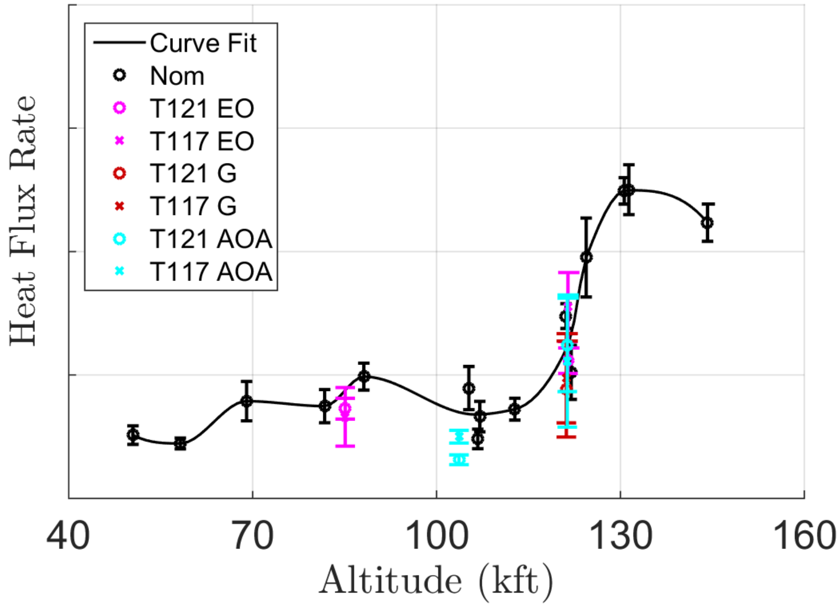
Engine Mounted Heat Shield Nominal



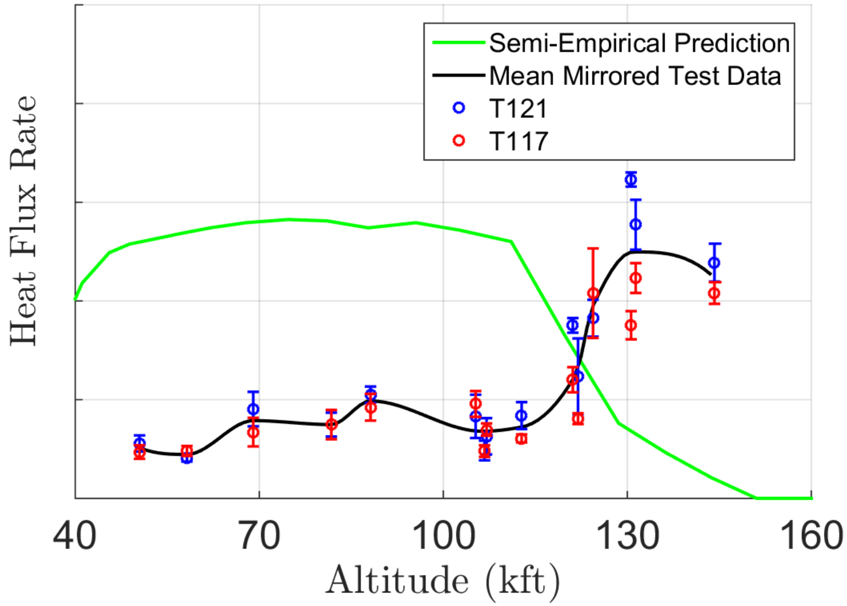


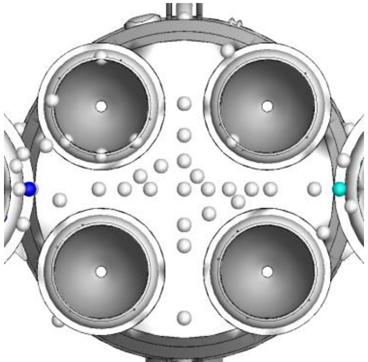
Base Heating – Altitude Profile: Inboard SRB

Booster Aft Skirt Lip Aft Face Off-Nominal



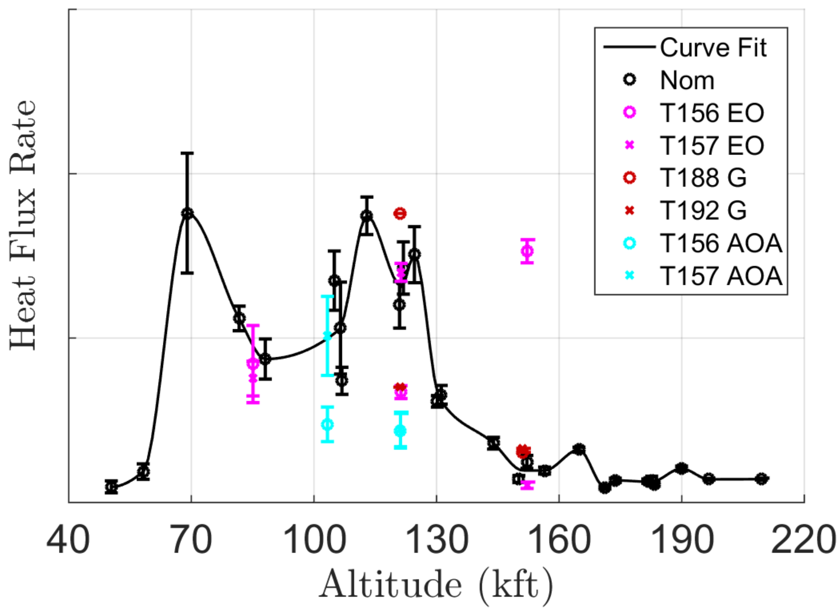
Booster Aft Skirt Lip Aft Face Nominal



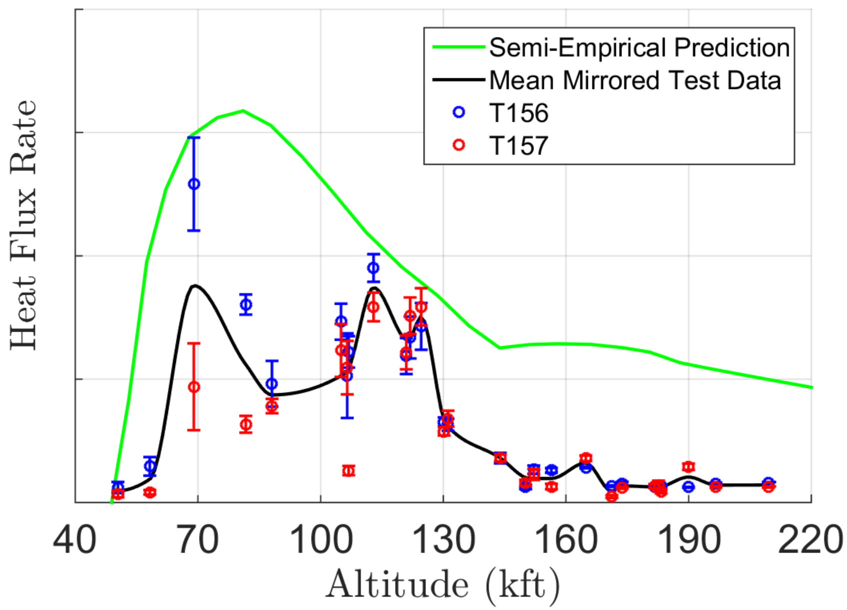


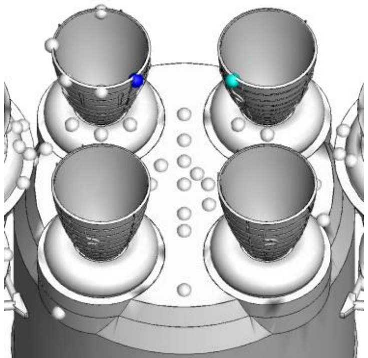
Base Heating – Altitude Profile: RS-25 Nozzle

Core Stage Engine Nozzle Off-Nominal



Core Stage Engine Nozzle Nominal



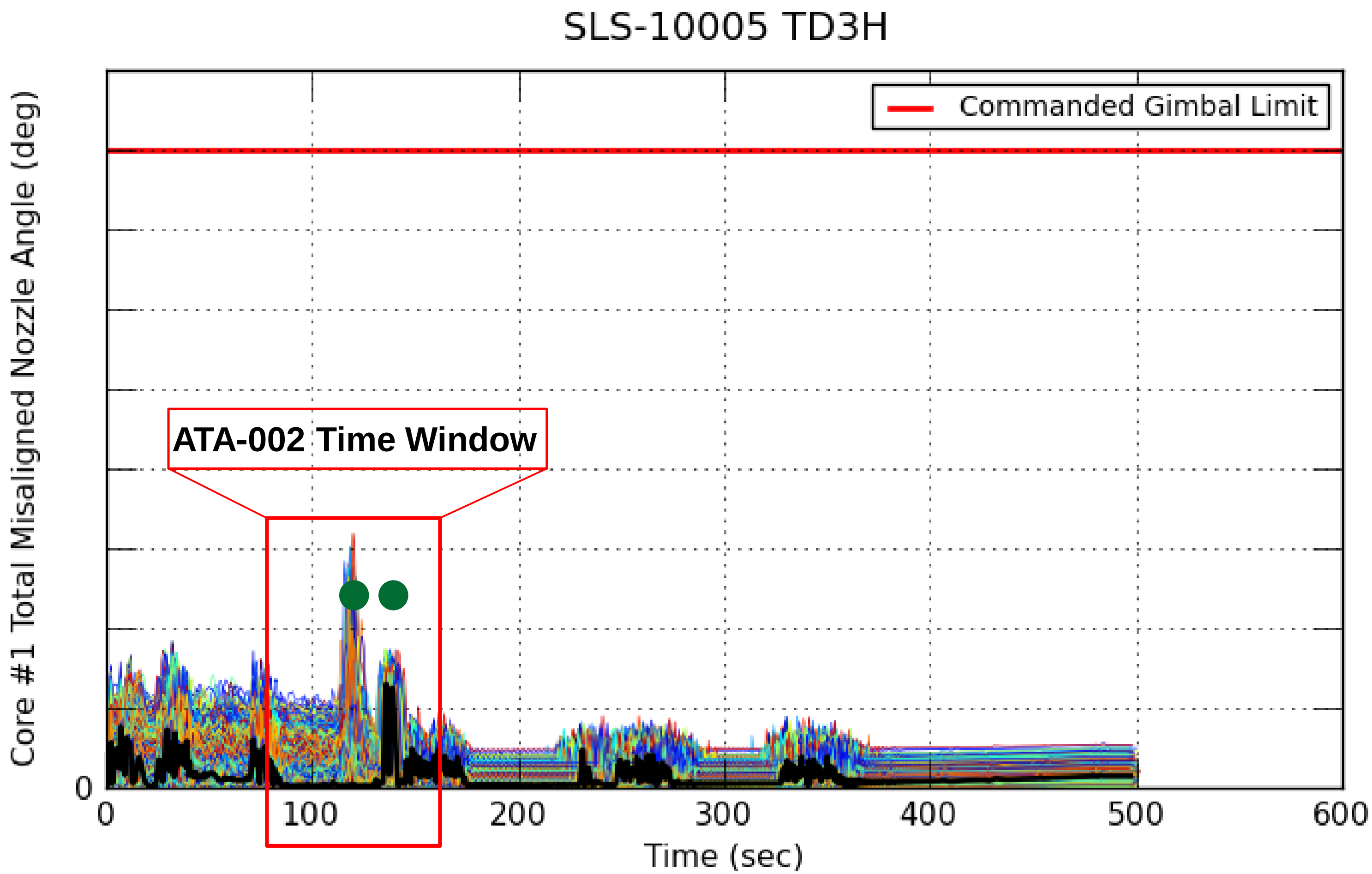


Base Heating Scaling Method

For proper scaling, it's important to match: $Pr,\ T_c,\ T_r,\ \left(\frac{P_{lip}}{P_\infty}\right)$

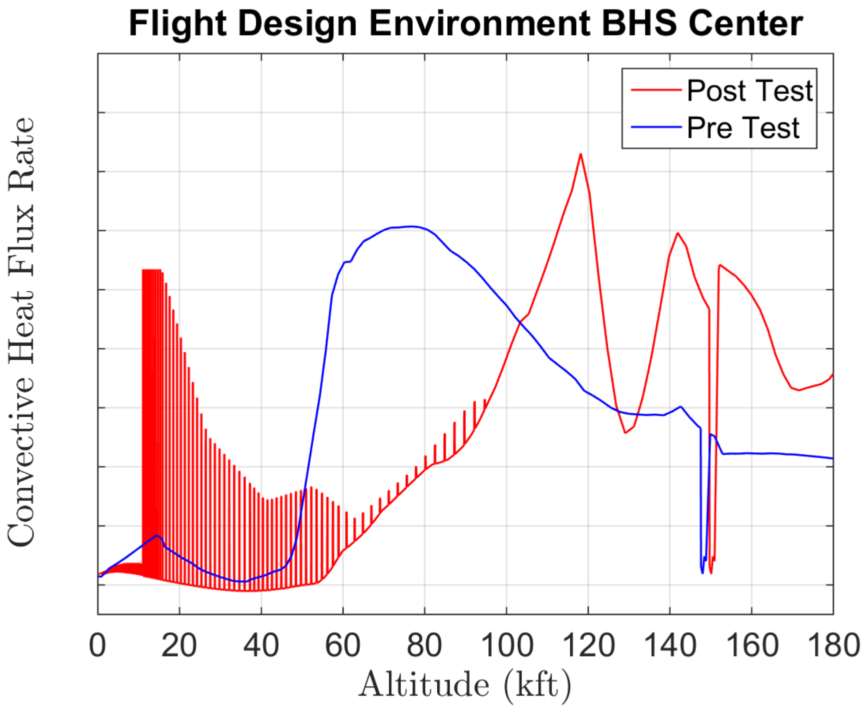
- $Nu = C\, Re^m Pr^n$
- $Nu = \frac{hL}{k}$
- $\frac{hL}{k} \propto Re^m Pr^n$
- $Re = f(P, L)$
- $h \propto P_c^m\, L^{m-1}$
- $h_F = h_T \left(\frac{P_{c,F}}{P_{c,T}}\right)^m \left(\frac{L_F}{L_T}\right)^{m-1}$
- $\dot{q}_F = \dot{q}_T \left(\frac{P_{c,F}}{P_{c,T}}\right)^m \left(\frac{L_F}{L_T}\right)^{m-1}$

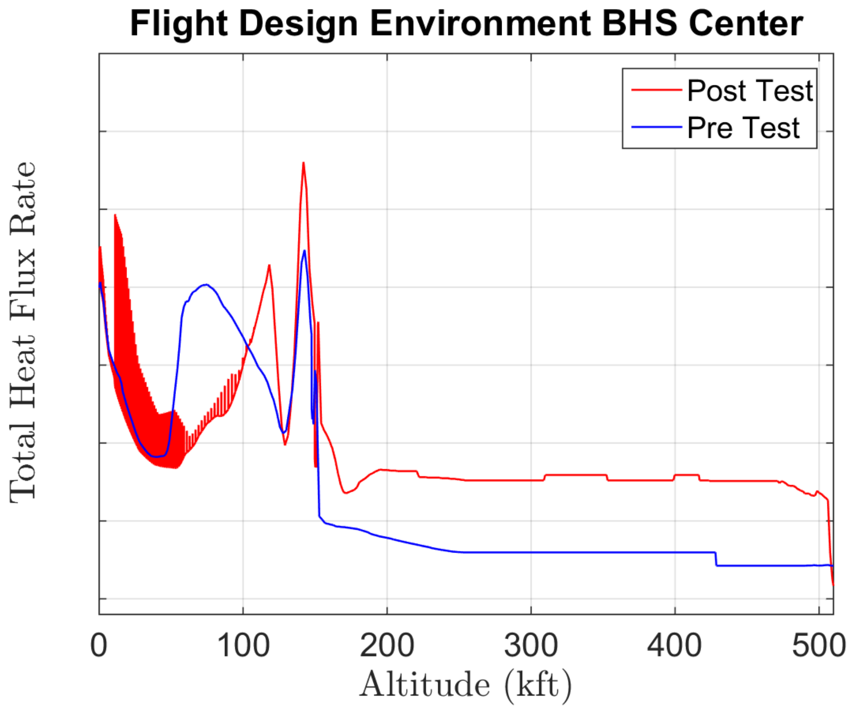
SLS Vehicle Maneuvers

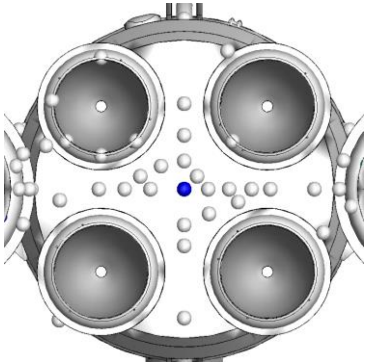


● ATA-002 Gimbal Test Runs

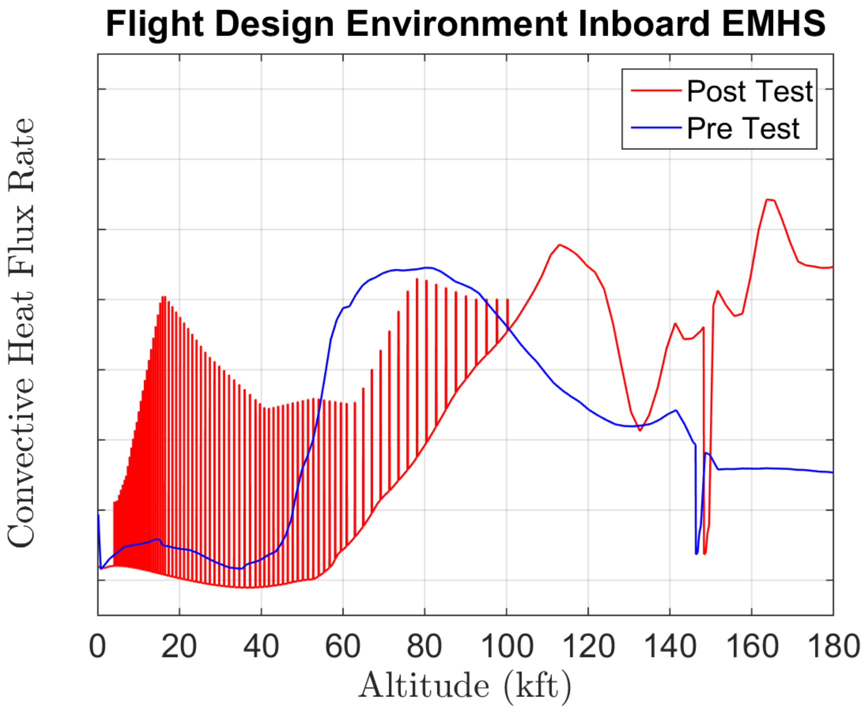
Design Environment: BHS Center

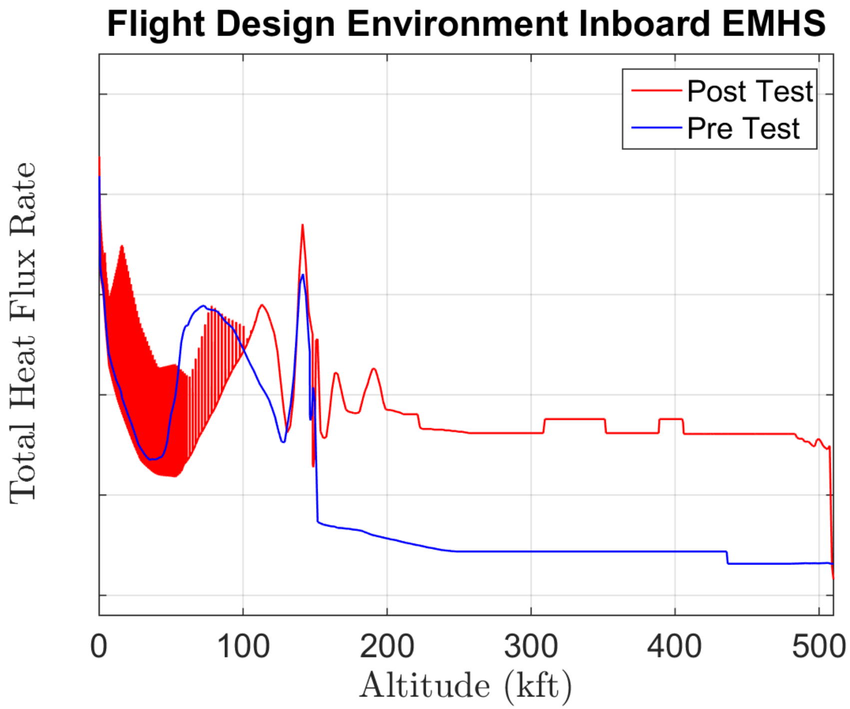


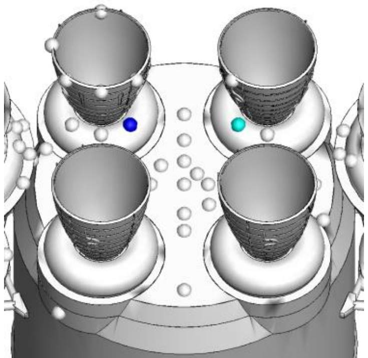




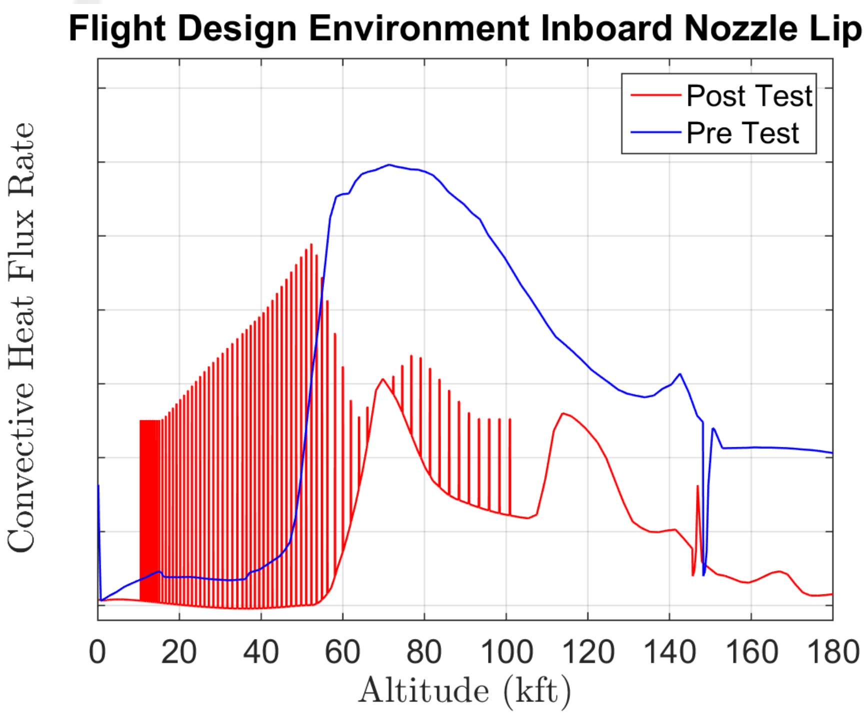
Design Environment: Inboard EMHS

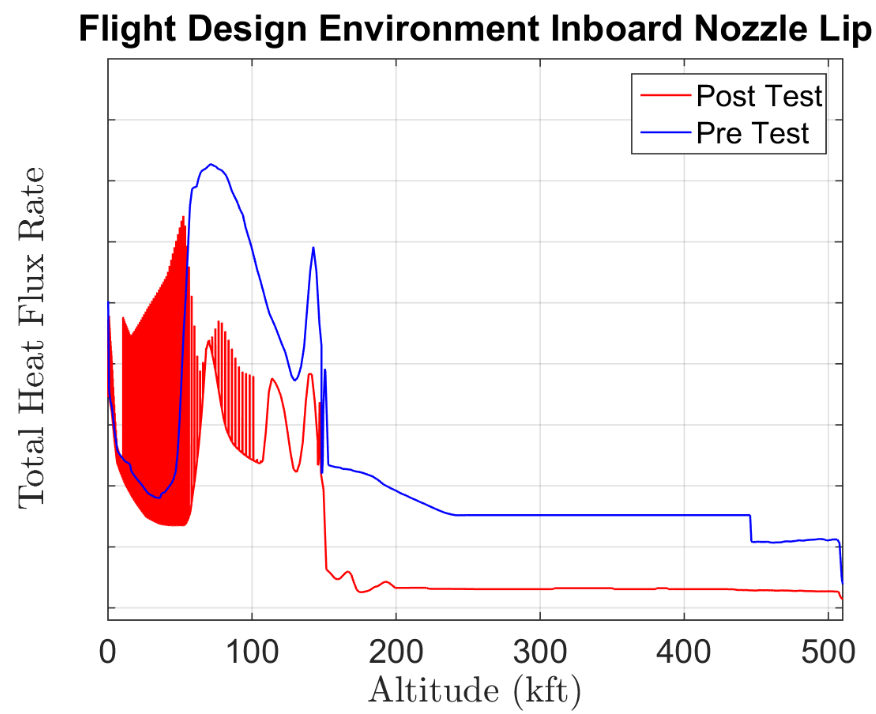


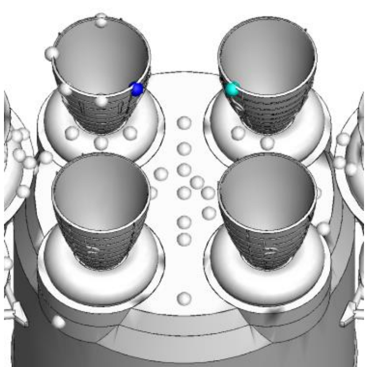




Design Environment: Inboard Nozzle Lip







Conclusions

- Successfully established a working theory of the flow physics and generated base heating design environments

- SLS base flow physics is dependent on:
  - Plume flow physics coupling between SRB and RS-25 plumes
  - RS-25 and SRB plume dynamics with freestream
  - Base Configuration

- Design environments show highest heating rate and heat loads at the:
  - Base Heat Shield center
  - Inboard Engine Mounted Heat Shield

- NASA and Boeing are currently working on SLS base TPS design

References

- [1]Mehta, M. et al (2014), Space Launch System (SLS) Pathfinder Test Program: Sub-scale booster solid rocket motor development for short-duration testing, NASA MSFC Spacecraft & Vehicle Systems Department EV33 Tech. Memo 14-024, Aerosciences Branch (EV33), Huntsville, AL, December 2014.
- [2]Mehta, M. et al (2014), Space Launch System (SLS) Pathfinder Test Program: Sub-scale core-stage rocket engine development for short-duration testing, NASA MSFC Spacecraft & Vehicle Systems Department EV33 Tech. Memo 14-023, Aerosciences Branch (EV33), Huntsville, AL, October 2014.
- [3]Dufrene, A.T. et al (2016), Space Launch System Base Heating Test: Experimental Operations and Results, AIAA 2016-0546, 2016 AIAA SciTech Conference, San Diego, CA.
- [4]Morris, C.I. (2015), Space Launch System Ascent Aerothermal Environments Methodology, AIAA 2015-0561, 2015 AIAA SciTech Conference, Kissimmee, FL.
- [5]Mehta et al (2013), Numerical Base Heating Sensitivity Study for a Four-Rocket Engine Core Configuration, *JSR*, Vol. 50, No. 3.
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- [7]Bergman, T.L., A.S. Lavine, F.P. Incropera and D.P. DeWitt (2015), Fundamentals of Heat and Mass Transfer, John Wiley & Sons, Inc., Hoboken, NJ.
- [8]Mullen, C.R., Bender, R.L., Bevill, R.L., Reardon, J., Hartley, L. (1972), Saturn Base Heating Handbook, NASA Technical Report, NASA-CR-61390, TD-050

Acknowledgements

- NASA MSFC Aerosciences Aerothermodynamics Team
- NASA MSFC Propulsion Thermal Analysis Branch
- CUBRC Aerosciences/LENS Team
- NASA SLS Project Office

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